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# Accelerated Corrosion Analysis of Aluminum Armor Alloy 2519 With Nonchromate Conversion Coatings for DOD Applications

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# Abstract

This study examines the effectiveness of six nonchromate conversion coatings on aluminum armor alloy 2519. Evaluation methods included ASTM B117 salt fog, General Motors 9540P cyclic salt spray, wet adhesion, and dry adhesion on painted test panels with initial salt fog screening of unpainted panels. Large differences in behavior were noted between the salt fog data and the cyclic salt spray data obtained on scribed panels. How these data may affect the implementation of nonchromate pretreatments for military vehicles such as Crusader and the Armored Amphibious Assault Vehicle (AAAV) considering aluminum 2519 is discussed.

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# 1. Introduction

Nonchromate conversion coatings to be tested were selected in conjunction with industry standards by following a model used in the National Center for Manufacturing Sciences (NCMS) study of nonchromate conversion coatings and our previous study [1, 2]. Based on initial feedback from the Bradley (M2) Infantry Fighting Vehicle Environmental Management Team (EMT) committee meeting in February 1998, six vendors of nonchromate coatings were asked to coat test panels. Although aluminum armor alloys 7039 and 5083 were specified by the committee, aluminum alloy 2519 was also examined and is the focus of this report. All vendors of the respective pretreatments agreed to have their coatings evaluated. The Alodine 1200 chromate conversion coating which was applied at Letterkenny Army Depot, Chambersburg, PA, and grit-blasted specimens supplied by Concurrent Technologies Corporation (CTC), were also included for control purposes.

# 2. Experimental Procedure

One hundred thirty aluminum panels of alloy 2519-T87 (each nominally 10 cm $\times$ 15 cm $\times$ 0.6 cm) were machined from rolled armor plate stock and sent to vendors and Army depots for coating application. Thirteen panels with each conversion coating combination were prepared. From each set of 13 panels, 11 were painted with an epoxy primer [3] and Chemical Agent Resistant Coating (CARC) [4] topcoat, and 2 panels were left in the unpainted conversion coated state. The duration between conversion coating application and initial application of primer varied due to the pretreatment completion times and the subsequent shipping times. Some vendors, including Sanchem, specified that the primer application follow within 24 hr of pretreatment. None of the pretreatments tested were coated within the 24-hr constraint. The specimen pretreatment numerical notations used were:

0 – Grit Blast

1 – Alodine 1200

2 – Alodine 2000

3 – Alodine 5200

4 – Organo Silane

5 – Brent

6 – Sanchem

7 – Trivalent Chromate (from Naval Air Warfare Center [NAWC])

8 – 8-mil Aluminum Thermal Spray (AL TSP)

9 – 4-mil AL TSP

The designations were die-engraved onto the panels allowing precise identification of the specimens at each phase of testing.

Salt fog testing in accordance with the American Society for Testing and Materials (ASTM) standard B117-90 [5], MIL-C-81706 [6], and MIL-C-5541E [7] was used to screen unpainted conversion coated panels as well as the CARC-coated panels. The solution used was the standard 5% NaCl. The panels with conversion coating only were visually monitored and rated for pitting, general corrosion, and staining (Table 1). Any uniform pitting beyond one or two random pits was considered a failure. All panels were photographed prior to testing, upon significant changes, and at failure (or the suspension of testing at 336 hr). CARC-painted panels (three each) for each conversion coating were exposed for 2,000 hr of salt fog under conditions identical to those for the unpainted specimens. These panels were scribed with an "X" using a standard carbide-tipped hardened steel scribe. Figure 1 shows a representative photo of initial specimen appearance after scribing (all painted panels appeared visually identical before testing). Periodic observations were made, and damage was assessed chronologically using a series of ratings based upon scribe corrosion, blistering, and any delamination or lifting of the paint from the substrate (Table 2). Final detailed ratings for the 2,000-hr duration were assessed using ASTM D-1654-79A [8] which quantitatively indicates the damage caused by pitting or delamination outwards from the scribe (Table 3).

A cyclic corrosion test chamber (CCTC) was used to evaluate painted test panels. For each conversion coating tested, five primed and topcoated CARC panels were subjected to CCTC testing. As in salt fog, the panels were scribed with an X. The scribed panels were

**Table 1. Ratings for 168 Hr ASTM B117-90 [5] Salt Fog Test on Unpainted Panels**

| Pass | Fail |
|---|---|
| PO = no spots | F1 = 6 to 50 spots |
| P1 = 1 spot | F2 = 50 spots to 33% corroded area |
| P2 = 2 spots | F2 = 50 spots to 33% corroded area |
| P3 = 3 spots | F2 = 50 spots to 33% corroded area |
| P4 = 4 spots | F2 = 50 spots to 33% corroded area |
| P5 = 5 spots | F2 = 50 spots to 33% corroded area |

placed in the chamber and tested using General Motors (GM) Standard Test 9540P [9], Method B, which provided a more realistic accelerated environmental test than conventional salt fog. The standard 0.9% NaCl, 0.1% $CaCl_2$, 0.25% $NaHCO_3$ test solution was used. In addition, standard plain carbon steel calibration coupons, described in GM-9540P [9] and supplied by GM, were initially weighed and subsequently monitored for mass loss at intervals set by the specification. Mass losses measured for steel coupons used for this test were within the parameters stated in the GM specification. The 9540P test consisted of 18 separate stages that included the following: saltwater spray, humidity, drying, ambient, and heated drying. The environmental conditions and duration of each stage for one complete 9540P cycle are given in Table 4. The panels were photographed or digitally scanned prior to testing, upon significant observations, and at the suspension of testing after 120 cycles. As with B117 salt fog, the extent of damage was assessed both chronologically and at the conclusion of exposure using the same methods.

Outdoor exposure was initiated on two panels of each conversion coating at the outdoor test site located at Cape Canaveral, FL (Figure 2). Long-term performance data will be obtained and presented at future Bradley EMT meetings and published in subsequent U.S. Army Research Laboratory (ARL) technical reports.

**Figure 1. Scribed Painted Test Panel (Initial).**

**Table 2. Chronological Accelerated Corrosion Test Rating Method for Painted Test Panels**

| Pass/Fail Ratings | |
|---|---|
| Pass | Fail |
| PO = No damage | F1 = Blistering on edges of scribe |
| P1 = White products in scribe from exposed substrate (no blisters) | F1 = Blistering on remaining nonscribe area |
| | F1 = Scribe and nonedge blisters |
| | F1 = Total failure<br>a) Excessive large blisters<br>b) Rupturing of blisters |

**Table 3. Corrosion Damage Assessment–ASTM D-1654-79A [8]**

| Rating of Failure at Scribe (Procedure A)<br>Representative Mean Creepage From Scribe | | |
|---|---|---|
| Millimeters | Inches (Approximate) | Rating Number |
| Over 0 | 0 | 10 |
| Over 0 to 0.5 | 0 to 1/64 | 9 |
| Over 0.5 to 1.0 | 1/64 to 1/32 | 8 |
| Over 1.0 to 2.0 | 1/32 to 1/16 | 7 |
| Over 2.0 to 3.0 | 1/16 to 1/8 | 6 |
| Over 3.0 to 5.0 | 1/8 to 3/16 | 5 |
| Over 5.0 to 7.0 | 3/16 to 1/4 | 4 |
| Over 7.0 to 10.0 | 1/4 to 3/8 | 3 |
| Over 10.0 to 13.0 | 3/8 to 1/2 | 2 |
| Over 13.0 to 16.0 | 1/2 to 5/8 | 1 |
| Over 16.0 to more | 5/8 to more | 0 |

**Table 4. GM-9540P [9] Cyclic Corrosion Test Details**

| Interval | Description | Interval Time (min) | Temperature (±3 °C) |
|---|---|---|---|
| 1 | Ramp to Salt Mist | 15 | 25 |
| 2 | Salt Mist Cycle | 1 | 25 |
| 3 | Dry Cycle | 15 | 30 |
| 4 | Ramp to Salt Mist | 70 | 25 |
| 5 | Salt Mist Cycle | 1 | 25 |
| 6 | Dry Cycle | 15 | 30 |
| 7 | Ramp to Salt Mist | 70 | 25 |
| 8 | Salt Mist Cycle | 1 | 25 |
| 9 | Dry Cycle | 15 | 30 |
| 10 | Ramp to Salt Mist | 70 | 25 |
| 11 | Salt Mist Cycle | 1 | 25 |
| 12 | Dry Cycle | 15 | 30 |
| 13 | Ramp to Humidity | 15 | 49 |
| 14 | Humidity Cycle | 480 | 49 |
| 15 | Ramp to Dry | 15 | 60 |
| 16 | Dry Cycle | 480 | 60 |
| 17 | Ramp to Ambient | 15 | 25 |
| 18 | Ambient Cycle | 480 | 25 |

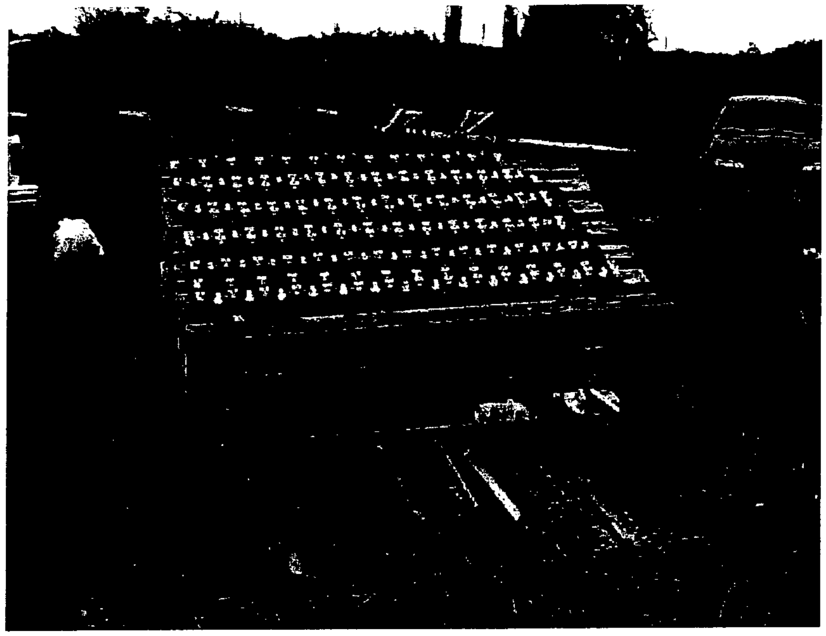


**Figure 2. Aluminum Armor Test Panels at Cape Canaveral Outdoor Exposure Site.**

Paint adhesion for both primed and topcoated panels was determined by using a wet adhesion test (Method 6301.2 [10] of standard MIL-C-81706 [6]). In this test, a standard adhesive tape was used to check adhesion on painted specimens after soaking for 24 hr in deionized water. After soaking, each panel was removed and then quickly dried. Two parallel scribes 1 in apart were made within the first minute after removal. Tape was uniformly applied across the scribes and immediately removed. Upon removal, any evidence of paint separation was noted by visual observation of both the panel and the tape. MIL-C-81706 [6] describes adhesion, based on a pass or fail system. To receive a "pass" rating, there must be no separation of the paint from the substrate or between layers of the paint. Additionally, a more detailed rating in accordance with ASTM D-3359 [11] was used (Table 5).

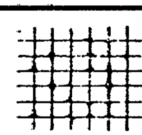
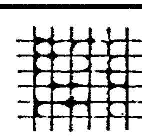
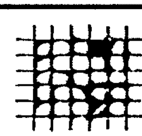
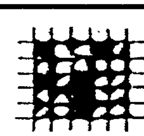
Dry adhesion measurements were in accordance with ASTM D-3359 [11] which employed a $6 \times 6$ grid of perpendicular scribes spaced at 2-mm intervals. Standard tape, as similarly used in wet adhesion, was uniformly applied over the cross-hatched area and immediately removed. Upon removal, any evidence of paint separation was noted by visual observation of both the panel and the tape. The rating method for ASTM D-3359 [11] is described in detail in Table 6.

**Table 5. Wet Adhesion Rating–Method ASTM D-3359 [11]**

| Rating | Description of Coating After Tape Removal |
|---|---|
| 5[a] | No peeling or removal |
| 4 | Trace peeling or removal along scribes |
| 3 | Jagged removal along scribes up to 1/16 in (1.6 mm) on either side |
| 2 | Jagged removal along most of the scribes up to 1/8 in (3.2 mm) on either side |
| 1 | Removal from most of the area between the scribes under the tape |
| 0 | Removal beyond the area of the scribes |

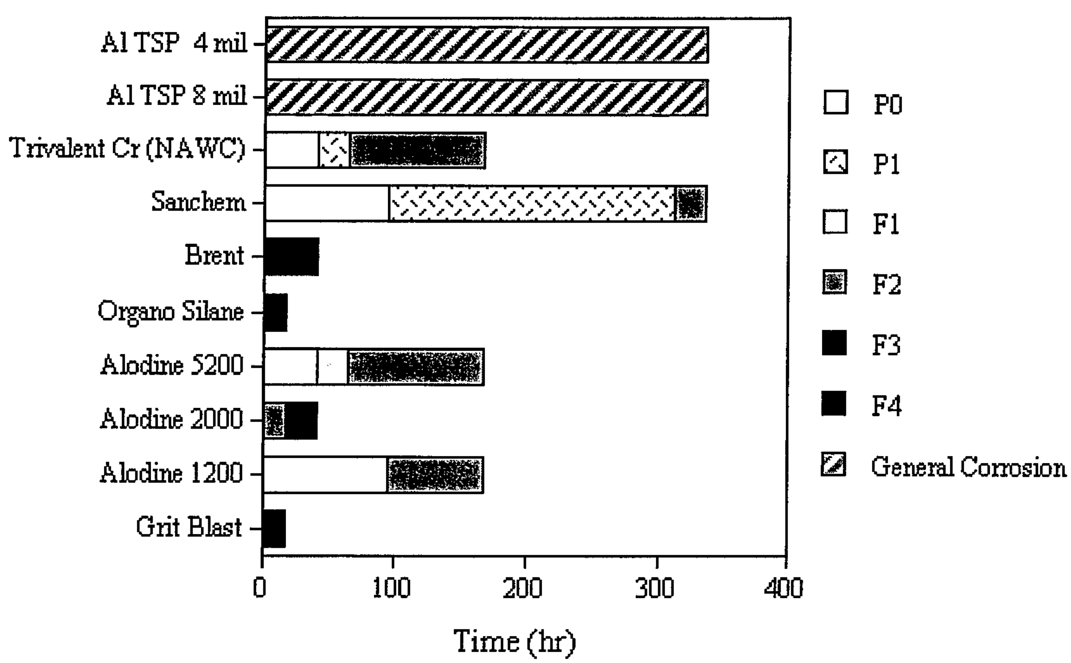
[a] Passes Military Performance Criteria

**Table 6. Dry Adhesion Rating (1X–ASTM D-3359) [11]**

| Classification | Surface of Cross-Cut Area Where Flaking Has Occurred (Example for 6 Parallel Cuts) |
|---|---|
| 5 | None |
| 4 |  |
| 3 |  |
| 2 |  |
| 1 |  |

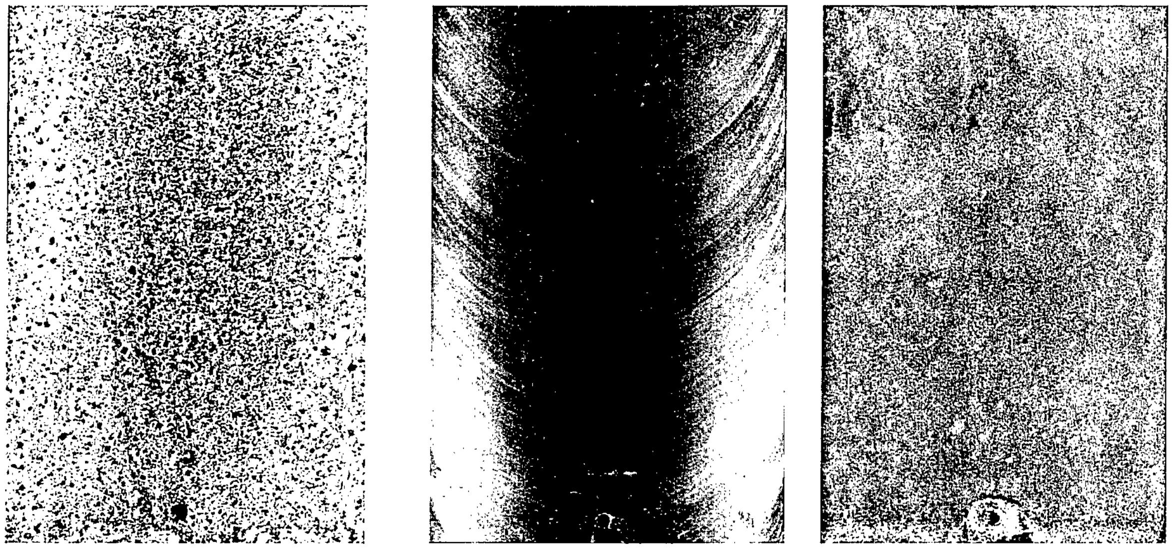
# 3. Results

**3.1 Salt Fog (ASTM B117-90 [5]).** The unpainted pretreated panels were periodically observed (Figure 3) and assigned one of the rating codes in Table 1. As was found in the National Center for Manufacturing Sciences (NCMS) [1] study for 2024 and a previous ARL study of 2519 [2], performance was substandard for all pretreatments tested. Even the chromate control panels did not meet the 336-hr qualification standard of MIL-C-81706 [6]. As a result, the screening was terminated at 168 hr. Four panel sets (Grit Blast, Alodine 2000, Organo Silance, and Brent) showed numerous pits after only 18 hr of exposure (Figure 4). The best salt fog performance on 2519 was seen for Sanchem-treated panels and the chromate Alodine 1200 control (Figure 4), which lasted through 312 hr and 168 hr, respectively, before light pitting was observed. The AL TSP panels showed large amounts of general surface corrosion with the generation of some hydroxide gel corrosion products; however, there was no pitting throughout the 336-hr duration (Figure 4). The remaining panels, Alodine 5200 and Trivalent Chromate from NAWC, finished in the intermediate range with more widespread pitting. Figure 5 shows the incremental salt fog performance for scribed painted panels.




*Showed numerous pits after only 18 hr exposure

**Figure 3. ASTM B117-90 [5] Salt Fog Performance of Unpainted Panels.**



Organo Silane at 18 hr:
Heavy Pitting

Alodine 1200 at 168 hr:
Light Scattered Pits

Al TSP 8 mil at 336 hr:
General Corrosion

**Figure 4. Corrosion Damage of Unpainted Salt Fog Panels.**

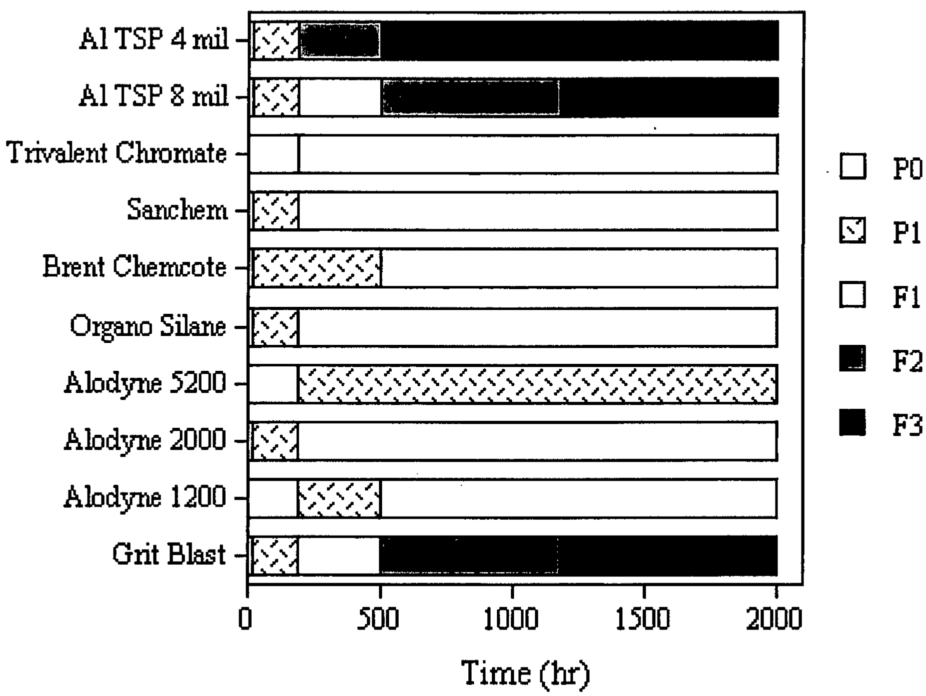



**Figure 5. Incremental Salt Fog Performance of Scribed CARC Panels.**

The assessment for the painted panels differs from the unpainted panels, as additional factors such as blistering and paint adhesion were considered. The performance metric for the painted panels is listed in Table 2. The primary failure mode for the painted panels was blistering along the scribe. The earliest blistering of the specimens occurred by 168 hr. The first panels to blister were the Grit Blast, Alodine 2000, Organo Silane, Sanchem, Trivalent Chromate, and AL TSP in both 4- and 8-mil thicknesses (Figure 6). The Brent treatment and Alodine 1200 panels showed scribe blisters by 500 hr. Alodine 5200 showed excellent performance and was able to endure the full 2,000 hours with no blistering (Figure 6). The final corrosion damage assessments per ASTM D-1654-79A [8] at 2,000 hr, including the data range for each set of the three panels, is given in Figure 7.

Alodine 5200 at 2,000 hr — Grit Blast at 504 hr — Al TSP 4 mil at 504 hr

**Figure 6. Salt Fog Corrosion Damage of Scribed CARC-Painted Panels.**

**3.2 Cyclic Corrosion Test Chamber (CCTC) (GM-9540P [9]).** All painted panels were subjected to 120 cycles of GM-9540P [9]. Chronological performance for each pretreatment through the cyclic exposure is shown in Figure 8. The assessment used for 9540P was identical to the assessment for ASTM B117-90 [5] salt fog for painted specimens (Table 2). As in salt fog, the failure mode for the painted panels was blistering along the scribe. For the majority of the panels (Alodine 1200, Alodine 2000, Alodine 5200, Organo Silane, Brent, Sanchem, and Trivalent Chromate) blistering along the scribe was established

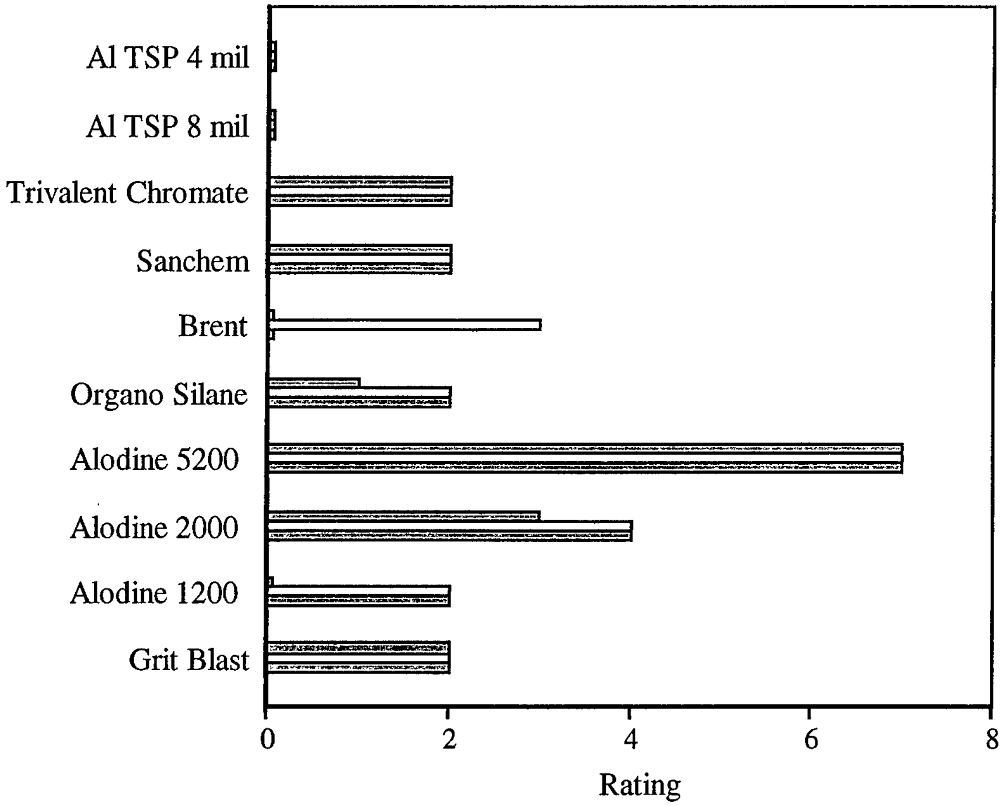



**Figure 7. Final 2,000 Hr Corrosion Assessment (ASTM D-1654-79A [8]).**

prior to 20 cycles. The grit-blasted specimens were marginally better blistering just after 30 cycles. The blistering, in general, was less severe than for salt fog, with only the Sanchem treatment displaying larger blisters. The Al TSP panels proved to be the superior treatment. The 4-mil-thick AL TSP began scattered light blistering at 100 cycles; however, the 8-mil specimens never blistered (Figure 9). The final corrosion damage assessments per ASTM D-1654-79A [8] at 120 cycles, including the data range for each of the five panels, is given in Figure 10.

**3.3 Wet Adhesion.** The data from the wet adhesion test is given in Figure 11, in accordance with ASTM D-3359 [11]. However, Federal Test Method Standard 141C–Method 6301.2 [10] used by the military, calls for no intercoat separation whatsoever at the scribe in either wet or dry testing, which corresponds to a "5" rating on the ASTM scale (Table 5). Most of the pretreatments showed good adhesion but did not pass the stricter

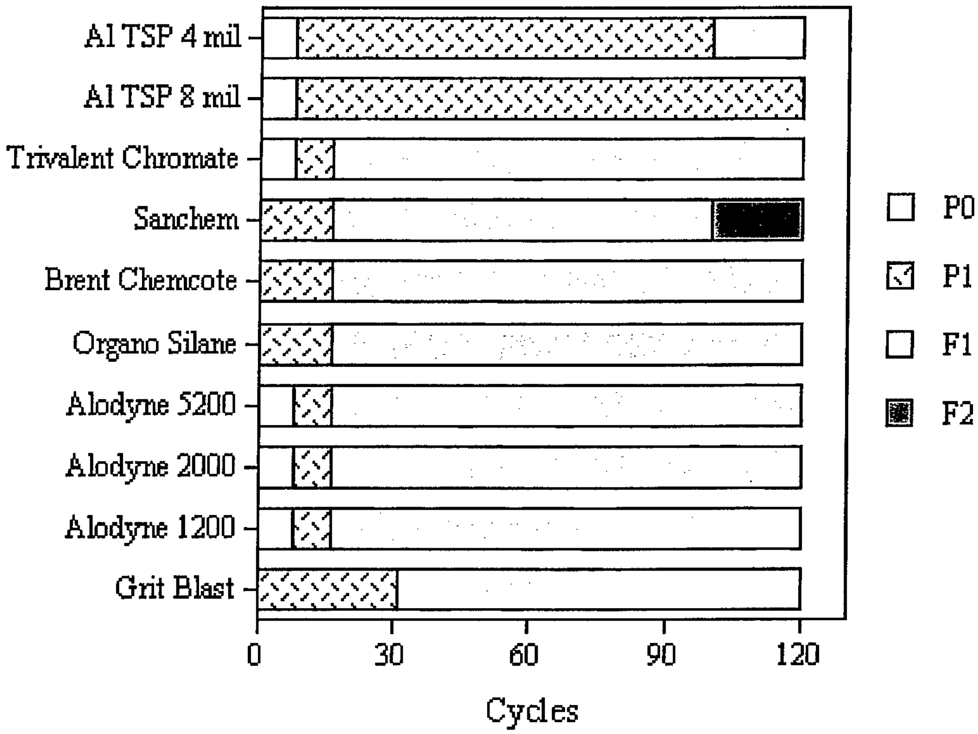
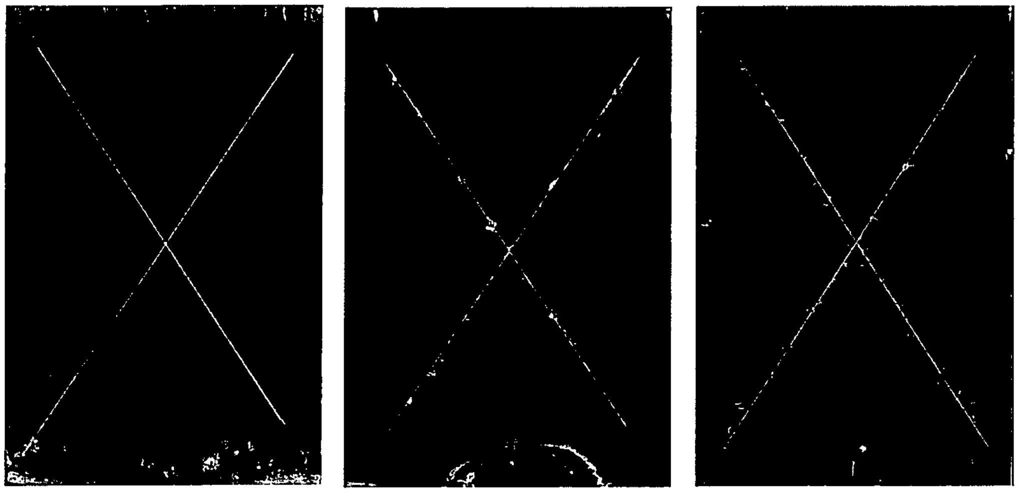



**Figure 8. Incremental Cyclic 9540P [9] Performance of Scribed CARC-Painted Panels.**

Federal standard. Panels which did well with a "4" rating but failed the Federal specification were Grit Blast, Alodine 1200, Sanchem, Trivalent Chromate, and 4-mil Al TSP. Panels that received the highest rating and passed the Federal standard were Alodine 5200, Organo Silane, Brent, and 8-mil Al TSP. Only the Alodine 2000 had delamination problems and finished with a "2" rating.

**3.4 Dry Adhesion.** The dry adhesion performance data for the panels, in accordance with ASTM D-3359 [11], is plotted in Figure 12. The dry adhesion test, by nature, is more severe than wet adhesion due to the mechanical nature of the scribes and their close proximity to each another. Due to this severity, a perfect score of "5" is much more difficult to attain. Five pretreatments earned a "4" rating: Alodine 5200, Organo Silane, Brent, 4-mil Al TSP, and 8-mil Al TSP. Grit Blast earned an intermediate rating of "3." Pretreatments that performed poorly included Alodine 1200, Alodine 2000, Sanchem, and Trivalent Chromate. Of the poor performers, all received "0" ratings except Alodine 1200 which was marginally better with a "1."



8-mil Al TSP at 120 Cycles Alodine 5200 at 120 Cycles Alodine 1200 at 120 Cycles

**Figure 9. Cyclic Corrosion Damage of Scribed CARC-Painted Panels.**

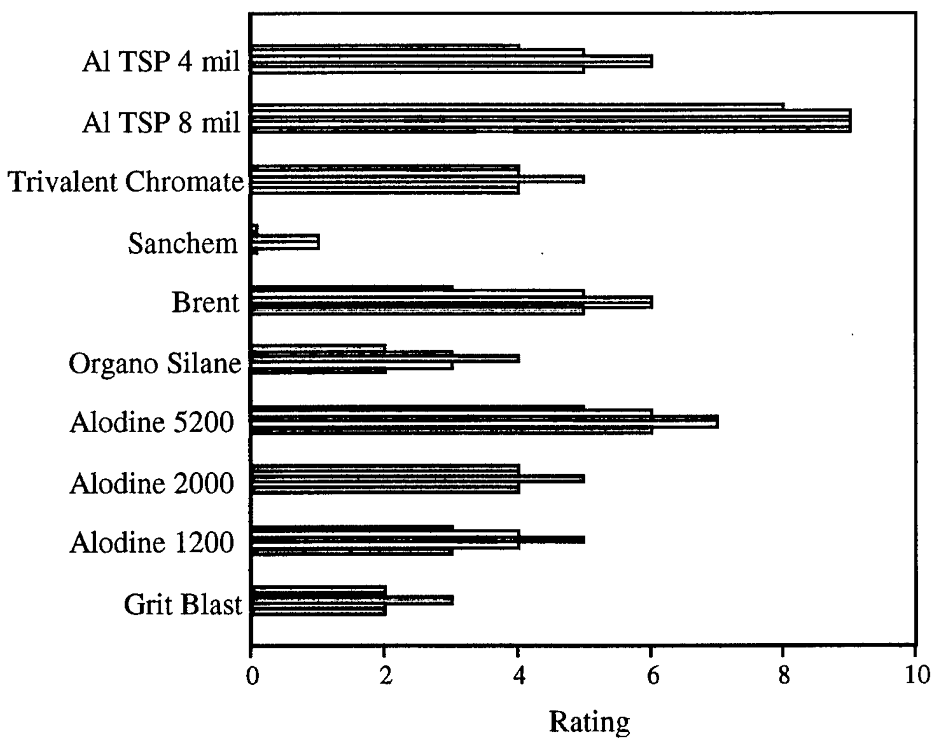



**Figure 10. Final 120-Cycle Corrosion Assessment (ASTM D-1654-79A [8]).**

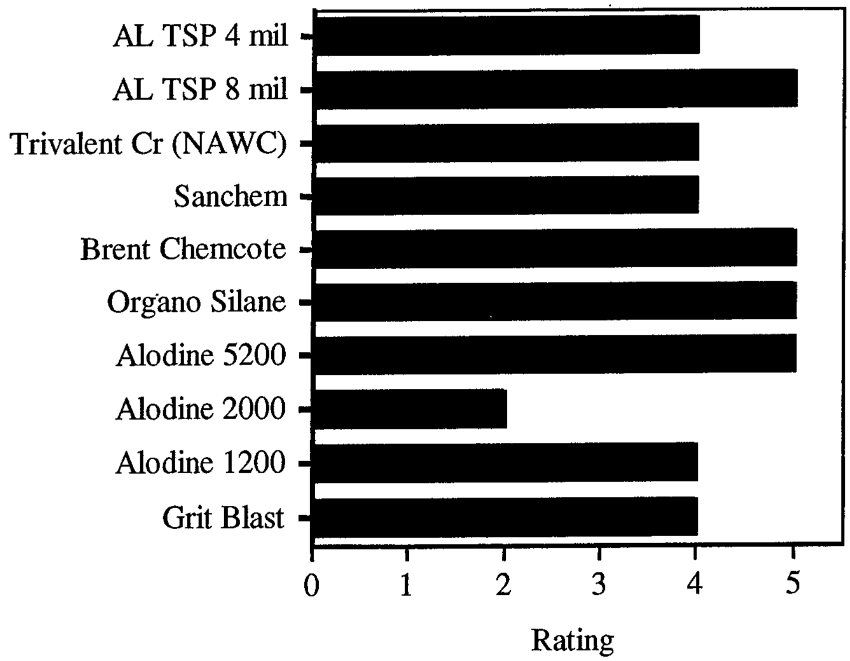



**Figure 11. Wet Adhesion Results (ASTM D-3359 [11]).**

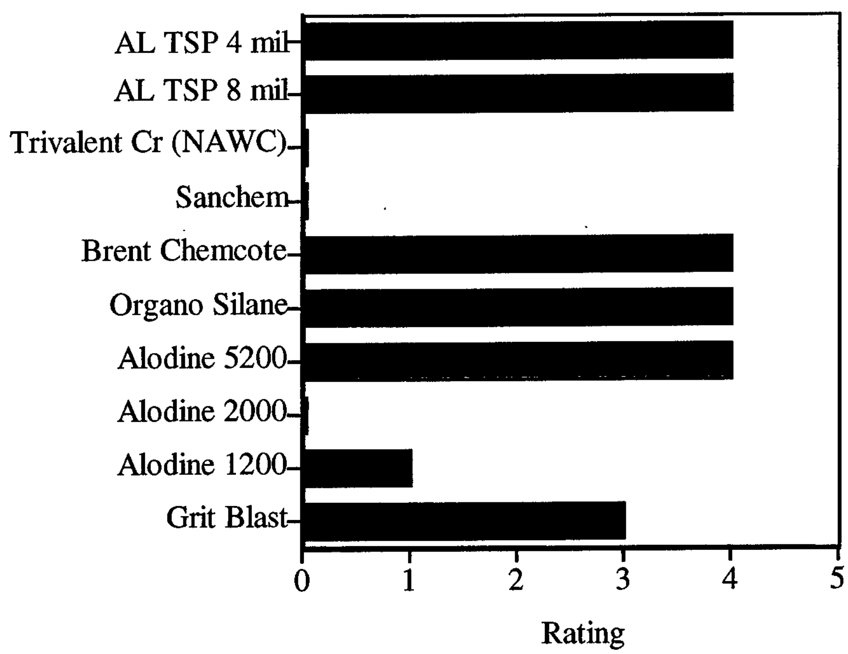



**Figure 12. Dry Adhesion Results (ASTM D-3359 [11]).**

# 4. Discussion

Aluminum alloys with copper such as Al 2024 and Al 2519 are difficult to protect from degradation due to their tendency to pit. In a previous ARL study [2] desirable properties of a pretreatment outlined included the following: (1) the presence of a uniformly distributed stabilized oxide layer at the metal surface, (2) an effective surface for adhesion of primer coats, (3) a contribution to the protective barrier of the entire coating system, and (4) inhibition of corrosion processes at coating holidays. The tests performed in this study measured these properties using several testing methodologies.

ASTM B117-90 [5] salt fog testing examined the degree of uniformity and porosity of the oxide layer and also revealed general information about the barrier properties of the conversion coating. The results in Figure 3 indicated that no single pretreatment (excluding Sanchem) is successful on Al 2519. The good performance of Sanchem was mainly due to barrier properties as will be discussed in the other tests. However, the effective barrier properties could be significant for applications where no organic coatings are subsequently applied and the probability of subsequent surface damage is low. It should be noted that the Al TSP coatings performed successfully and protected the Al 2519 substrate from corrosion attack by pitting. There was, however, a noticeable accumulation of general corrosion by such as an aluminum hydroxide-based gel. While pitting was prevented, the formation of these products could have adverse effects on overlying coatings or other mated components. This negative side effect became evident in the salt fog exposure of the scribed CARC-coated panels. In this case, the scribe allowed localized entry of the NaCl solution to the porous TSP coating. The porosity acted as a transport conduit for the corrosive solution and delamination and bulk blistering of the coating was evident by 168 hr. The ability of any pretreatment to retard corrosion at scratches and other holidays can drastically affect the performance of coating systems in the field. Army systems are especially prone to incidental damage of coatings, so this consideration is vitally important. The Sanchem treatment, which had performed effectively without a coating in salt fog screening, began scribe blistering at 168 hr and performed on par with the other treatments. In contrast, the Alodine 5200, which had failed in salt fog screening without paint, performed extremely well and did not blister throughout 2,000 hr with scribed CARC paint (Figures 3 and 5). Although nonchromate-based coating schemes may show "barrier" properties that exceed the chromated control panels, the conversion coating's ability to inhibit/heal corrosion at the scribed area is the critical factor which allows chromate-based conversion coatings to perform so well on many different alloys and in many environments.

For greater correlation with actual outdoor field environments encountered in service life, the GM-9540P [9] cyclic corrosion test was used. As in the 2,000-hr salt fog test on the coated specimens, the ability of a conversion coating to act as a barrier coat was not an indication of its effectiveness in an actual fielded environment where coatings can be compromised. The performance disparity noted between Sanchem in the 336-hr screening and the 2,000-hr coated salt fog test even more evident in 120 cycles of cyclic exposure where the Sanchem failed due to large blistering (Figures 3 and 8). Unexpectedly, Alodine 1200 also showed lower performance than expected vs. the initial 168-hr salt fog screening although relatively less than the Sanchem treatment. Alodine 5200 and the Brent pretreatment performed best among the conventionally applied pretreatments. Contrary to its performance in 2,000-hr salt fog, the Al TSP coatings showed performance gains of an order of magnitude vs. the other pretreatments. The superior performance was likely due to the long, 6-hr, 60 °C dry cycles inherent in GM-9540P [9] that limits the permeation and saturation of the corrosive solution within the porous TSP layer. It should be noted that while GM-9540P statistically is known to correlate better with actual atmospheric environments [12], the Al armor alloy in question is under consideration for use in marine environments. In these settings, the armor would be subjected to immersion in seawater and brackish solutions. This exposure would favor permeation into a damaged or improperly applied paint system and could potentially lead to corrosion problems evident in the 2000-hr salt fog exposure. Additional study of Al TSP permeation coating in saturation humidity is being conducted at ARL to find solutions mitigating these effects.

The adhesion tests indicated that most of the nonchromate coatings provided good adhesion of the organic primer and topcoat; exceptions included pretreatments of Alodine 2000 (wet and dry), Sanchem (dry) and Trivalent Chromate (dry). The catastrophic adhesion failure of Alodine 2000 in both tests indicated that the surface layer formed during the pretreatment does not promote adhesion with the CARC-coating system.

The ability of chromate to inhibit corrosion at coating defects should not be overlooked. Most developers of new nonchromate-based conversion coatings strive to achieve the 336-hr salt fog resistance required by the qualification standard of MIL-C-81706 [6] and will often quote much greater exposure times. It must be stressed that this level of performance can be attained with an effective defect-free "barrier" conversion coating that performs poorly at coating defects.

The poor results of some pretreatments in the tests with scribed CARC systems indicate a factor that is often neglected: MIL-C-81706 [6] is a standard for chromate conversion coatings and should not be considered a performance specification to qualify any nonchromate alternative. Because the Army (and the rest of the Department of Defense) is replacing military specifications with performance specifications, it is crucial to assess those factors which are critical to the performance of the entire coating system.

Utilizing the combination of cyclic corrosion tests, adhesion tests, and outdoor exposure remains the best method for assessing overall coating system performance.

# 5. Conclusions

- Two nonchromate conversion coatings, Alodine 5200 and Brent, performed as well as or better than standard $Cr^{+6}$-based Alodine 1200 on Al armor alloy 2519.

- The Al TSP coatings showed superior performance in GM-9540P [9] cyclic salt spray but were highly susceptible to attack at coating defects during continuous exposure in saturated humid environments.

- The "pass/fail" criteria in current military specifications for chromate conversion coatings should not be directly applied to nonchromate coatings. This was confirmed by wide disparities between ASTM B117-90 [5] salt fog and GM-9540P [4] cyclic salt spray results for many of the pretreatments.

- ASTM B117-90 [5] is still a beneficial standard for screening and is useful for analysis of coating systems when combined with a wider array of test methods including cyclic corrosion and adhesion.

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This study examines the effectiveness of six nonchromate conversion coatings on aluminum armor alloy 2519. Evaluation methods included ASTM B117 salt fog, General Motors 954OP cyclic salt spray, wet adhesion, and dry adhesion on painted test panels with initial salt fog screening of unpainted panels. Large differences in behavior were noted between the salt fog data and the cyclic salt spray data obtain on scribed panels. How these data may affect the implementation on nonchromate pretreatments for military vehicles such as Crusader and the Armored Amphibious Assault Vehicle (AAAV) considering aluminum 2519 is discussed.

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